United States
Department of
Agriculture

Forest Service

**Intermountain
Forest and Range
Experiment Station
Ogden, UT 84401**

Research Note
INT-327

April 1983

Using Rheology to Estimate Short-term Retardant Droplet Sizes

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Using Rheology to Estimate Short-term Retardant Droplet Sizes [1-3].

100 Wayne P. Van Meter[1]

ABSTRACT

Airtanker delivery of fire retardant fluids causes the dispersal of many gallons of liquid into a cloud of droplets that settles onto the fuel. Measurement of the viscosity, elasticity, surface tension, and density of the fluid allows an estimate of droplet size. This information is of use in explaining the performance of various retardants and in selecting the identities and concentrations of retardant components. Results are presented for five short-term retardants and one long-term retardant.

1 KEYWORDS: fire retardants, rheology, viscosity, airtankers 2

Fire retardant liquids applied by airtankers are dispersed over the fire area in a pattern whose size and coverage density are determined in a complex way by numerous variables. The pilot can control the location (altitude and direction of flight), the airspeed, and the volume (number of tank doors opened) of an application. Beyond that, the behavior of the retardant and the consequent effect on the course of the fire depend on the physical and chemical properties of the liquid. Whether the chemical influence on the combustion process has a chance to come into play depends on the distribution of the retardant over fuel surfaces. This, in turn, is determined primarily by the sizes of the droplets in the shower produced when the retardant is dropped from a speeding aircraft.

Rheology is a science dealing with the deformation and flow of matter, involving the measurement of forces required to cause such motion and the behavior of the specimen when the force is removed. Those physical properties of fluids that are of concern here include density, surface tension, viscosity, and elasticity. Recent reports (Andersen and others 1976; Van Meter and George 1981) have described the use of these properties, measured in the laboratory, in the estimation of droplet size for specific retardant materials released from aircraft moving at various airspeeds.

There are several types of laboratory instruments that can measure the visco-elasticity of a liquid over wide ranges of the rate-of-shear. In the present instance, a Haake Rotovisco RV2 is being used to gather data on several retardant products being used by or offered for use to government agencies for the control of wildfires. This instrument utilizes a cylindrical cup containing the test fluid, and a concentric rotor immersed in the fluid. A Fisher Tensiometer is employed to measure surface tensions, and 30-ml pycnometers are used to measure densities.

The results presented in this report describe several short-term retardants. These materials contain only water and a small amount of a thickening agent which imparts a useful level of viscosity and, usually, elasticity to the mixture. These properties are beneficial in at least three distinct ways. As the bulk liquid breaks up into droplets after being released from the aircraft, the average droplet size in the cloud is significantly larger than in the case of pure water. This results in more rapid fall and less wind drift. The larger droplet size and decreased diffusion within each drop result in much less evaporative loss of water. Finally, the thickened mixture adheres to fuel surfaces better than water, retaining the cooling capacity of the material where it is needed. Some short-term retardants also tend to creep over or drain down onto fuel surfaces more readily than do the current long-term products.

Retardant products of the long-term type (high salt content) have been empirically developed to maximize performance in the field. This has taken years of operational use. Recently, these materials have been tested in the laboratory, yielding droplet-size values in the 2-mm to 5-mm range for an airspeed of 120 knots. This droplet size range is a logical point of departure for systematizing the comparison of the performance of short-term retardants with that of long-term materials.

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The figures appended to this report show results of testing six materials—five short-term retardants and one long-term retardant. They are:

Material	Manufacturer
Absorbex 2020 SLS	Absorbent Polymers, Inc.
Fire-Kill II (Xanthan gum and Kelco polymer)	Sanitek Products, Inc.
Fire-Trol STP (Nalco) (Nalco synthetic polymer)	Chemonics Industries
Short-Stop (Henkel SPG 502S polymer)	Merryhill Company
Tenogum	Charles Tennant and Co.
Phos-Chek XA	Monsanto Industrial Chemicals Co.

PROCEDURES AND COMPUTATIONS

Test specimens were prepared by stirring weighed amounts of the concentrated product into distilled water. Entrainment of air was avoided (blenders are not appropriate), and stirring was continued until the mixture was homogeneous. Specimens were stored overnight in closed jars before use. The Phos-Chek samples had been supplied by the manufacturer, with the guar gum content adjusted to 42 percent, 100 percent, and 200 percent of the amount present in the normal XA product. A measured amount of the sample is poured into the viscometer cup, and the cup is then raised into position around the rotor. Measurements of viscosity can be made at incrementally increased values of constant rotation speed, or the opposing force can be recorded automatically as a function of linearly increasing rotation speed. The elasticity is measured by observing the extent of reverse rotation of the rotor (degrees of angle) caused by the "stretchiness" of the fluid, after a spline in the drive system is disconnected.

A computer program has been developed which utilizes measured values of the four properties mentioned above. The density and surface tension have single discrete values for any particular liquid, but the viscosity and elasticity of a thickened retardant solution change if the fluid is undergoing shearing movement, as when being poured or being torn apart by impacting air at a high velocity.

The result produced by the computation program is a plot of the mass median droplet diameter, d_m, as a function of the aircraft velocity, V_a. Obviously, droplets of many sizes will be present in the descending retardant cloud. The size, d_m, is such that half of the mass of the retardant in any particular tankful ends up in droplets smaller than d_m, the other half in larger droplets. Measurements made by the Rotovisco instrument are subject to two sources of error. The elasticity phenomenon manifests itself as a tension within the fluid as the molecules are distorted during shearing motion. This tension dissipates quickly when shearing ceases. When the rate of shear is very high, the time required for the Rotovisco clutch mechanism to stop the rotation of the rotor is comparable to that needed for the tension to disappear. Thus, some of the reverse rotation of the rotor is lost. Also, very low shear rates result in "plug flow," meaning that part of the fluid nearest the motionless cup is not moving (being sheared) at all, causing the perception of apparent viscosity to be too low. The computation program provides for the systematic exclusion of data points that might be influenced by either very high or very low shear rates.

RESULTS

The primary, and only necessary, presentation of results is the graph of mass median diameter against airspeed, discussed later. Other plots that show the differences between the several retardants tested have been prepared. These are arranged in three groups of six graphs each, each group portraying one aspect of the rheological properties of each of the six retardants. The graphs must be logarithmic because of the wide ranges of the numerical values.

The first two groups (fig. 1 to 12) deal with viscosity. The apparent viscosity is a quantitative measure of the force needed to cause shearing motion within a fluid. The dashed lines drawn through part of the shear-rate range show the estimated position of the curve for mixtures having the recommended use-level concentration. The short-term retardants, particularly Absorbex, Fire-Kill, and Fire-Trol, have noticeably lower viscosities than does the long-term Phos-Chek. (The viscosities, in poise units, are 4 to 7 times larger for Phos-Chek than for the others.) The effective viscosity graphs will be discussed later.

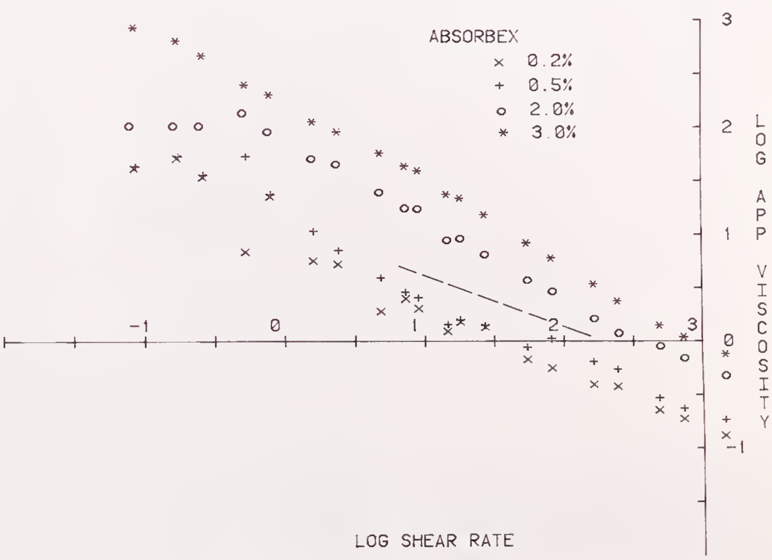

Figure 1.—Relationship of the apparent viscosity to the shear rate for several concentrations of Absorbex.

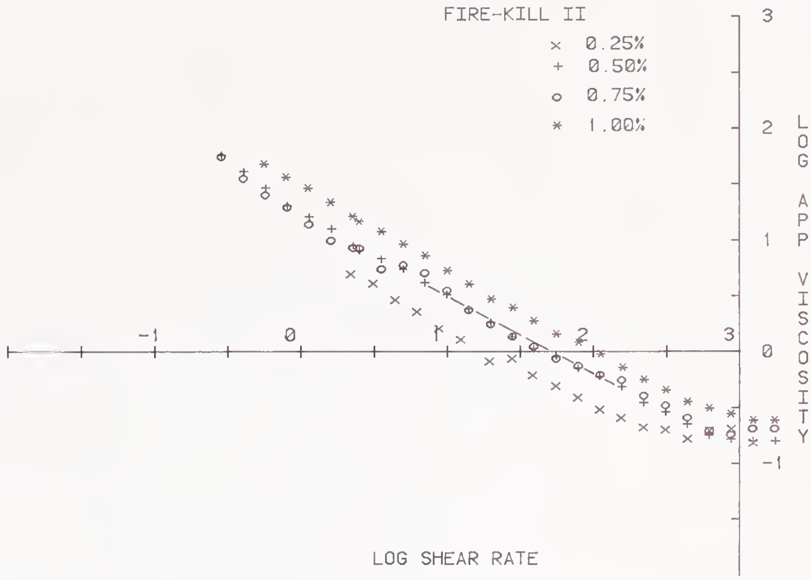

Figure 2.—Relationship of the apparent viscosity to the shear rate for several concentrations of Fire-Kill II.

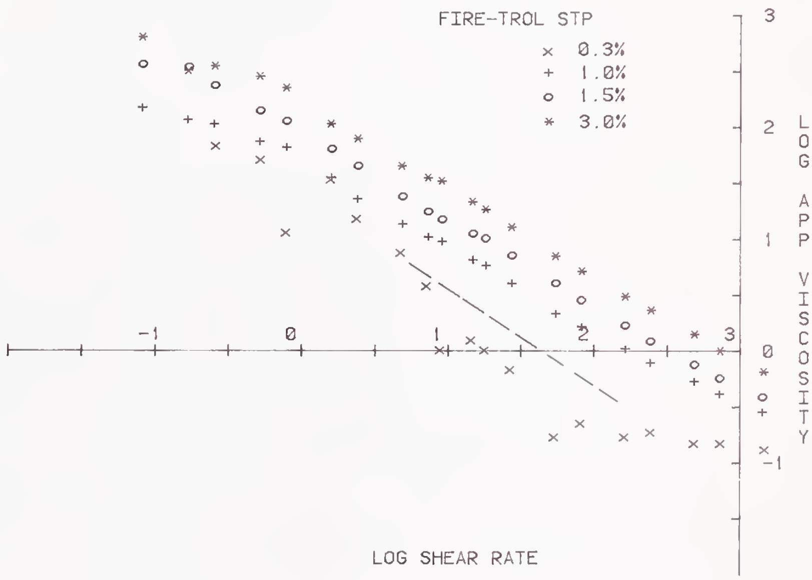

Figure 3.—Relationship of the apparent viscosity to the shear rate for several concentrations of Fire-Trol STP.

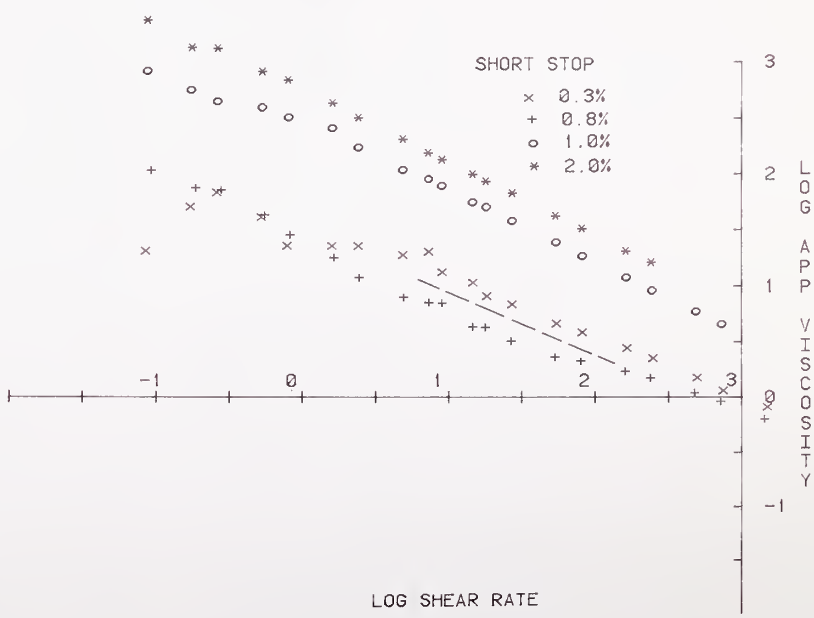

Figure 4.—Relationship of the apparent viscosity to the shear rate for several concentrations of Short-Stop.

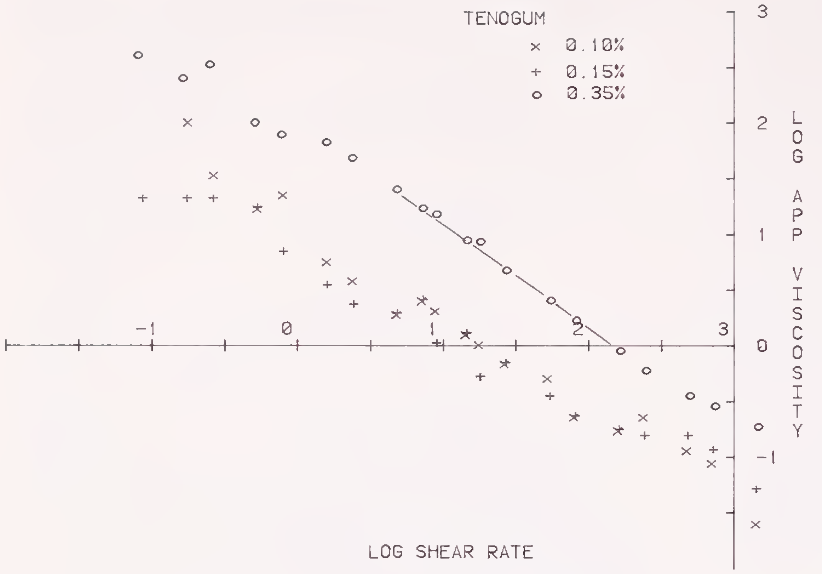

Figure 5.—Relationship of the apparent viscosity to the shear rate for several concentrations of Tenogum.

Figure 6.—Relationship of the apparent viscosity to the shear rate for three formulations of Phos-Chek XA.

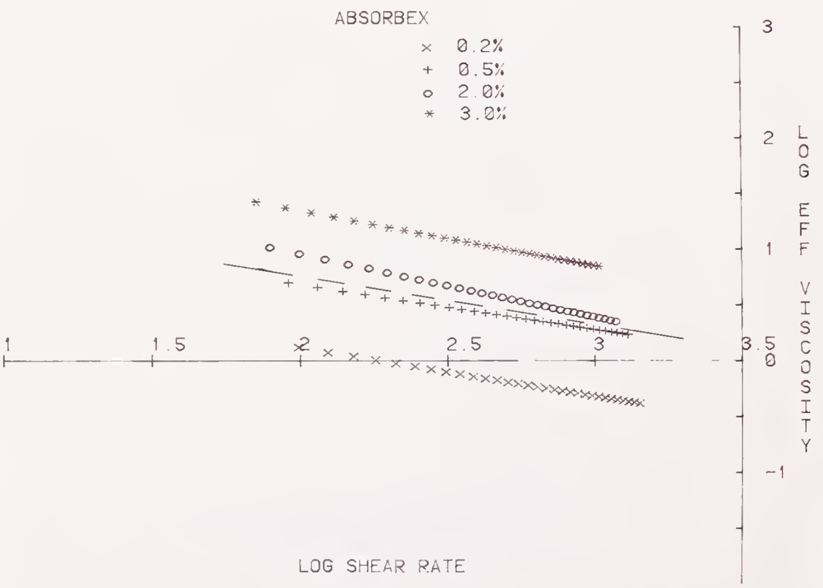

Figure 7.—Relationship of the effective viscosity to the shear rate for several concentrations of Absorbex.

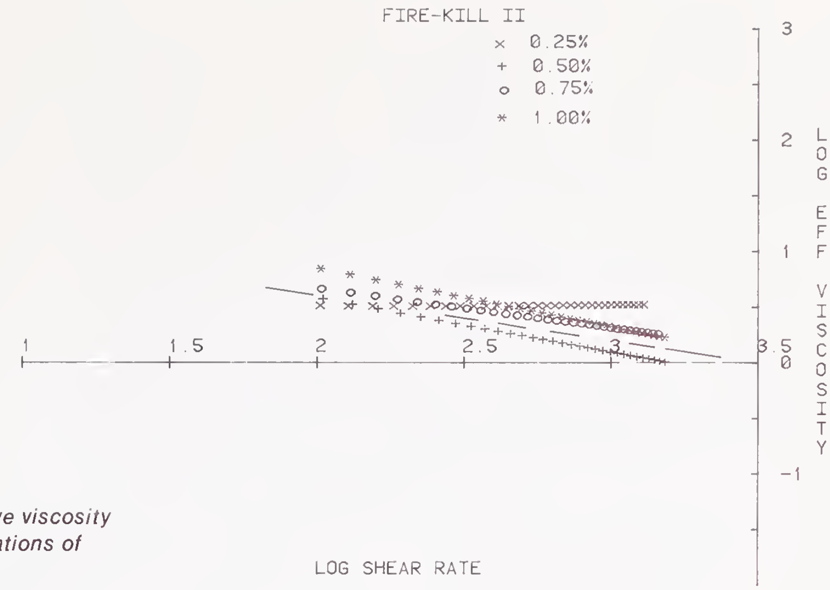

Figure 8.—Relationship of the effective viscosity to the shear rate for several concentrations of Fire-Kill II.

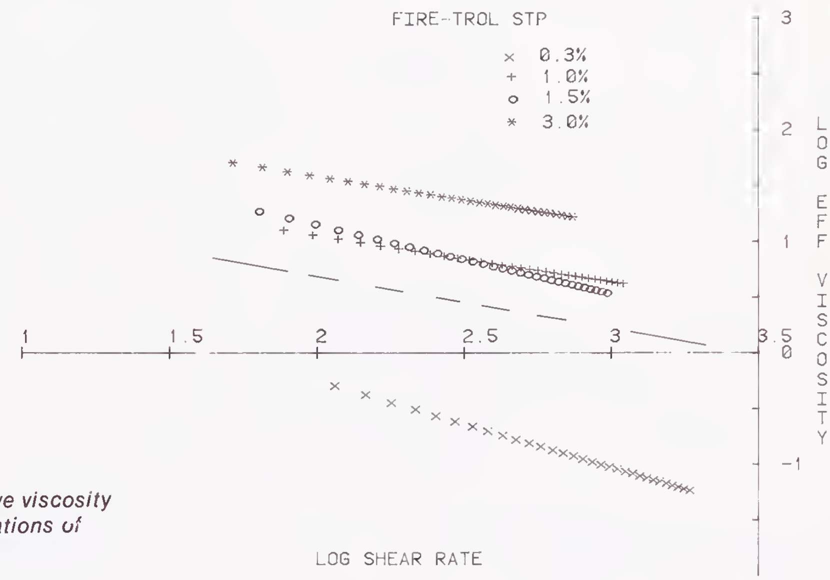

Figure 9.—Relationship of the effective viscosity to the shear rate for several concentrations of Fire-Trol STP.

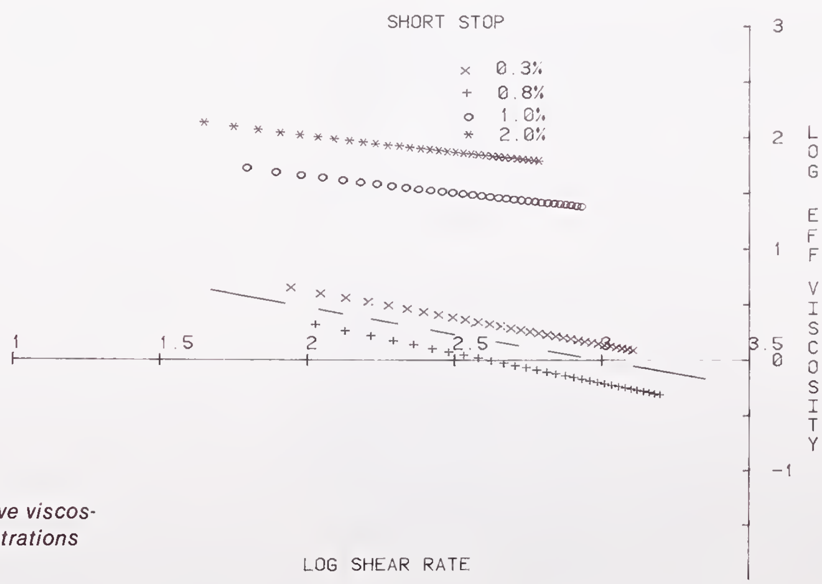

Figure 10.—Relationship of the effective viscosity to the shear rate for several concentrations of Short-Stop.

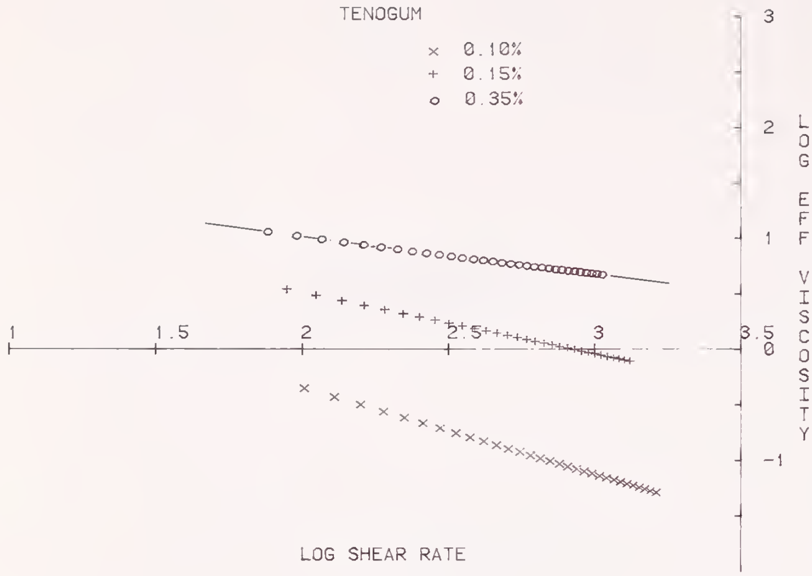

Figure 11.—Relationship of the effective viscosity to the shear rate for several concentrations of Tenogum.

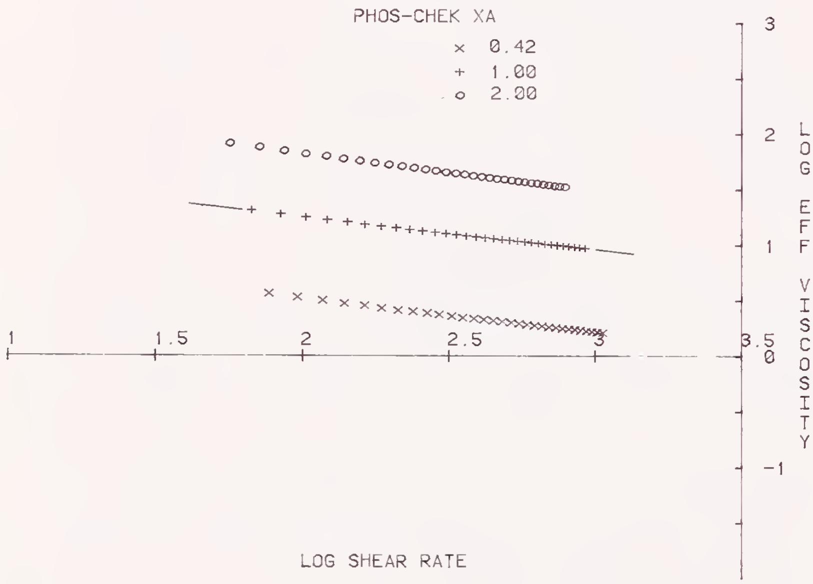

Figure 12.—Relationship of the effective viscosity to the shear rate for three formulations of Phos-Chek XA.

The property called recoverable shear (''rec shear'') is a measure of the elasticity of a fluid. From the general trends in figures 13 to 18, it is apparent that Fire-Kill II has surprisingly high elasticity. There are anomalies in the sequence of curve locations in the cases of Absorbex and Tenogum. The guar gum in Phos-Chek imparts a well-known stringiness to its behavior when drops separate, but the forces tending to cause recovery of shape after deformation are comparable to those of most of the short-term retardants.

The effective viscosity at any one rate of shear is determined by both the apparent viscosity and the elasticity. The plots in figures 7 to 12 are smoothed because the computation process uses a polynomial regression and a least-squares linear correlation to produce mathematical equations describing the relationships between apparent viscosity and shear rate, and between apparent viscosity and elasticity. Because these are exponential relationships, the log-log plots are linear. As before, the solid line segments show an estimate of the result to be expected from retardants containing recommended use levels of the concentrate.

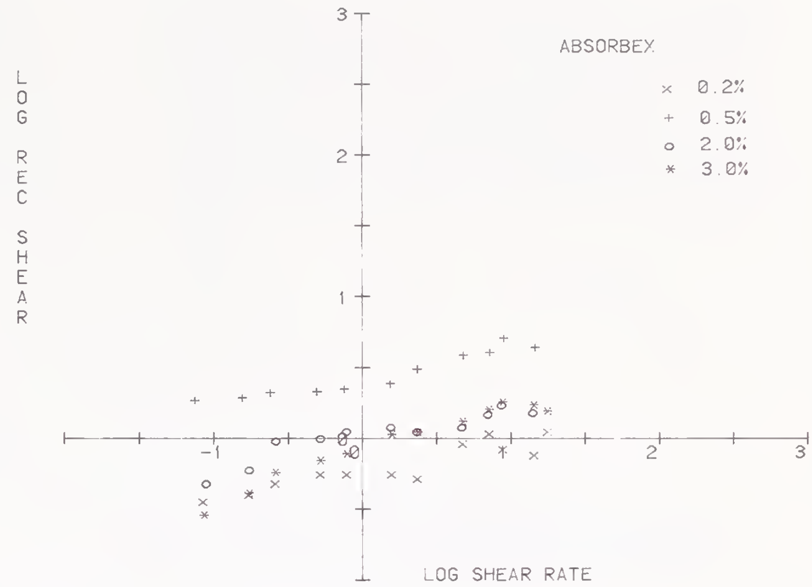

Figure 13.—Relationship of the elasticity or recoverable shear to the shear rate for several concentrations of Absorbex.

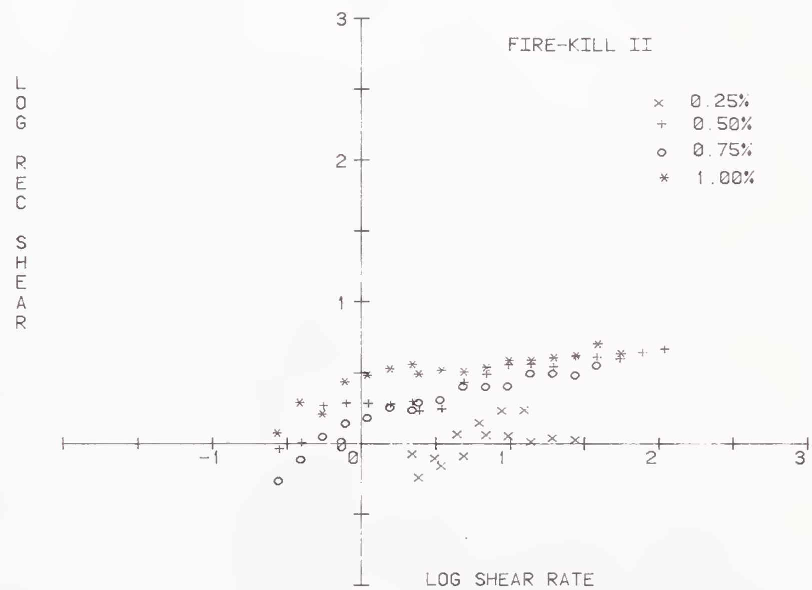

Figure 14.—Relationship of the elasticity or recoverable shear to the shear rate for several concentrations of Fire-Kill II.

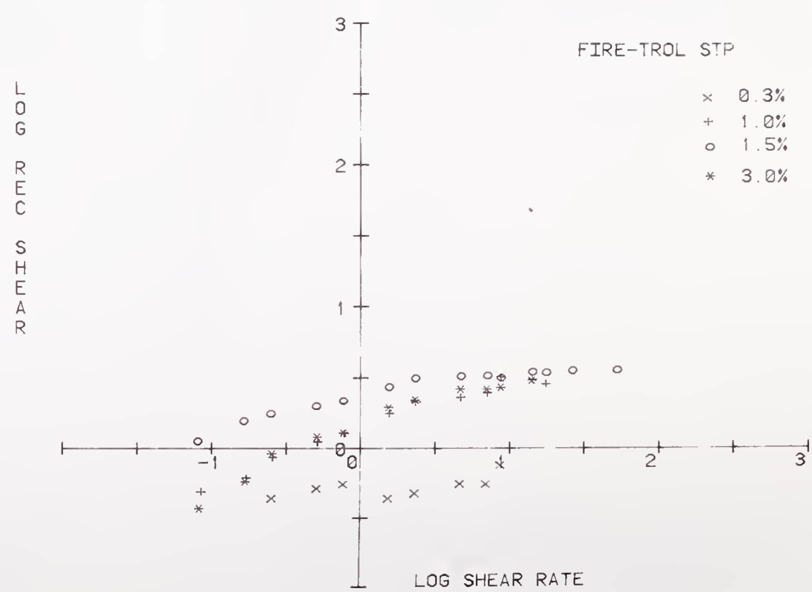

Figure 15.—Relationship of the elasticity or recoverable shear to the shear rate for several concentrations of Fire-Trol STP.

Figure 16.—Relationship of the elasticity or recoverable shear to the shear rate for several concentrations of Short-Stop.

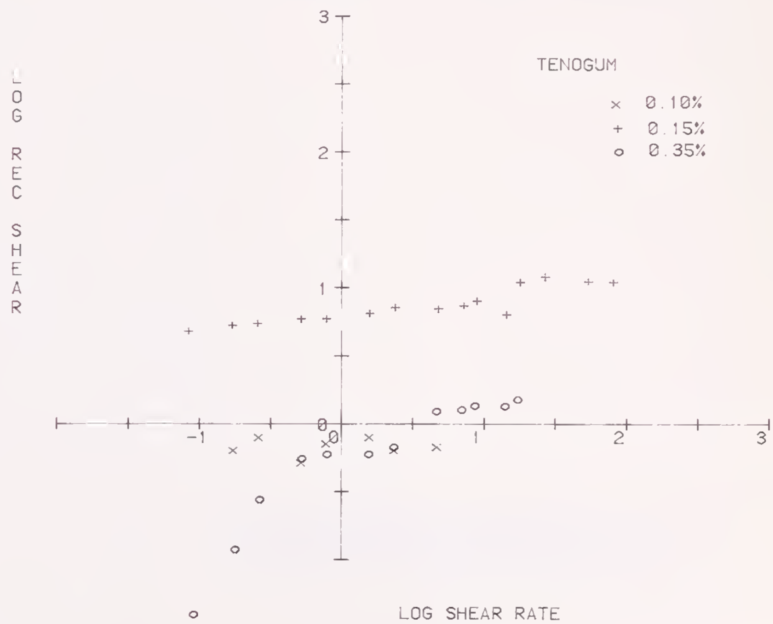

Figure 17.—Relationship of the elasticity or recoverable shear to the shear rate for several concentrations of Tenogum.

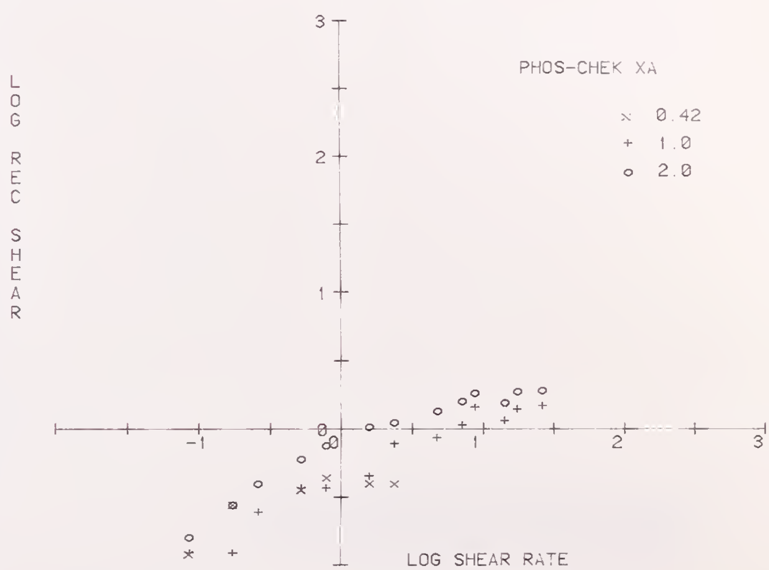

Figure 18.—Relationship of the elasticity or recoverable shear to the shear rate for three formulations of Phos-Chek XA.

Figures 19 to 25 predict the mass median droplet diameter, d_m, which would result from release of retardant at airspeeds between 30 and 180 knots. The forms of the equations that are solved to derive values of the d_m show that the apparent viscosity should be 2 to 10 times more important than the elasticity in determining the effective viscosity. The effective viscosity, with the density and surface tension, determines the mass median diameter. The experimental results confirm this, in that although Fire-Kill II and Fire-Trol STP have the highest values of elasticity (fig. 14 and 15), the fact that Short-Stop and Phos-Chek XA have the highest apparent viscosities (fig. 4 and 6) correlates with these two retardants also having the highest diameters (fig. 22 and 24). In examining the plots with respect to these comments, consider the performances at use level concentrations and the more usual fixed-wing airspeeds—90 to 120 knots.

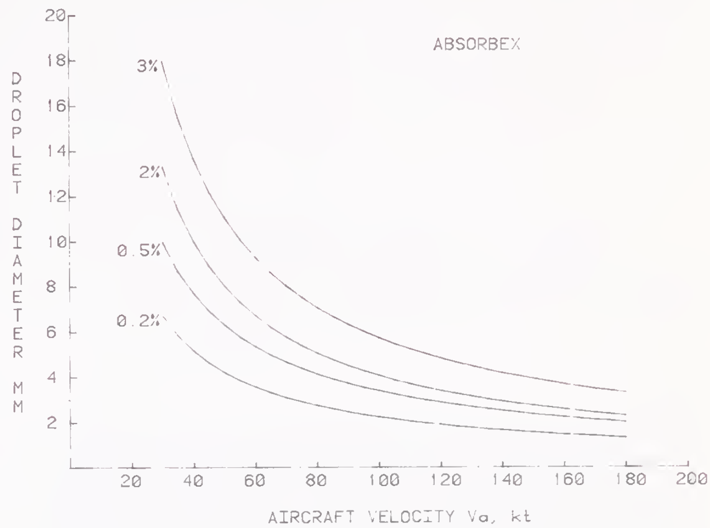

Figure 19.—Droplet diameter as a function of aircraft velocity for several concentrations of Absorbex.

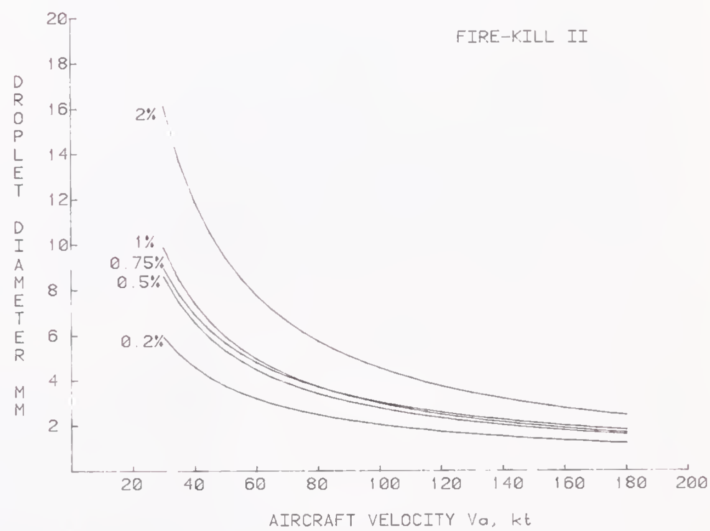

Figure 20.—Droplet diameter as a function of aircraft velocity for several concentrations of Fire-Kill II.

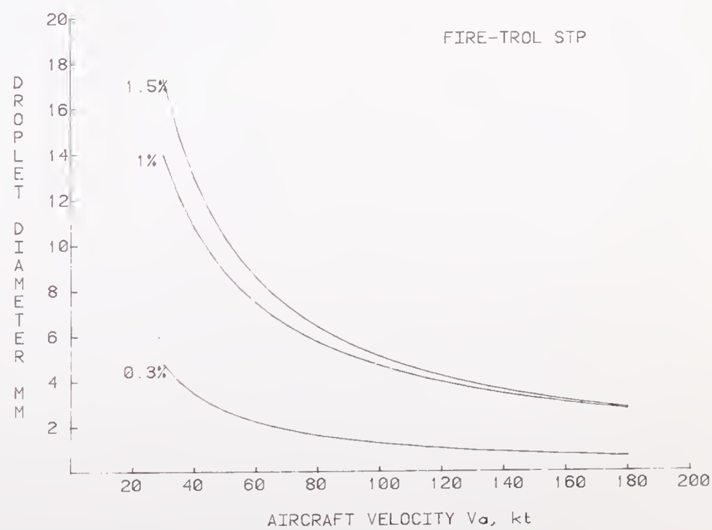

Figure 21.—Droplet diameter as a function of aircraft velocity for several concentrations of Fire-Trol STP.

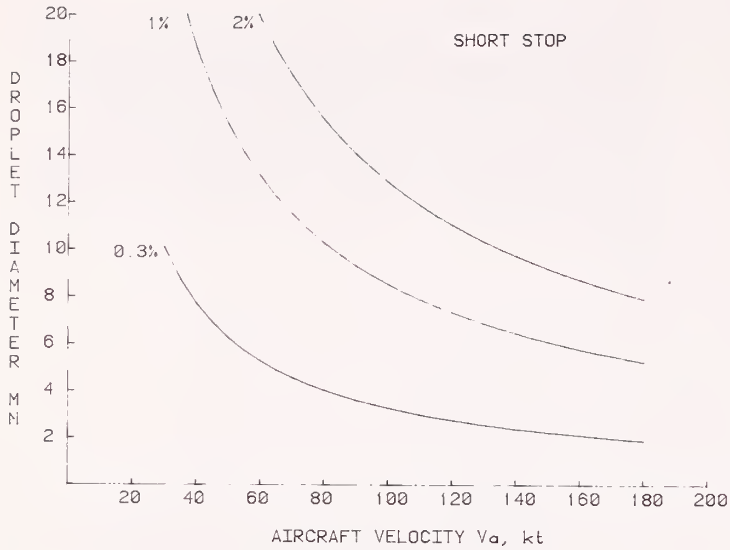

Figure 22.—Droplet diameter as a function of aircraft velocity for several concentrations of Short-Stop.

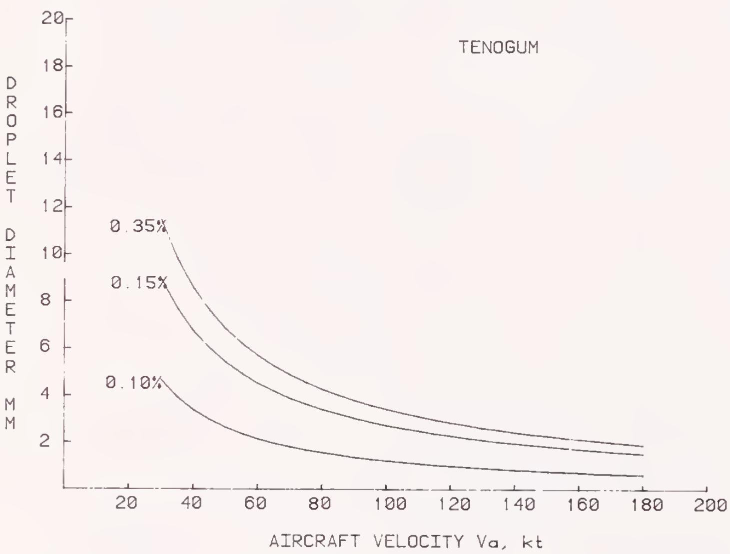

Figure 23.—Droplet diameter as a function of aircraft velocity for several concentrations of Tenogum.

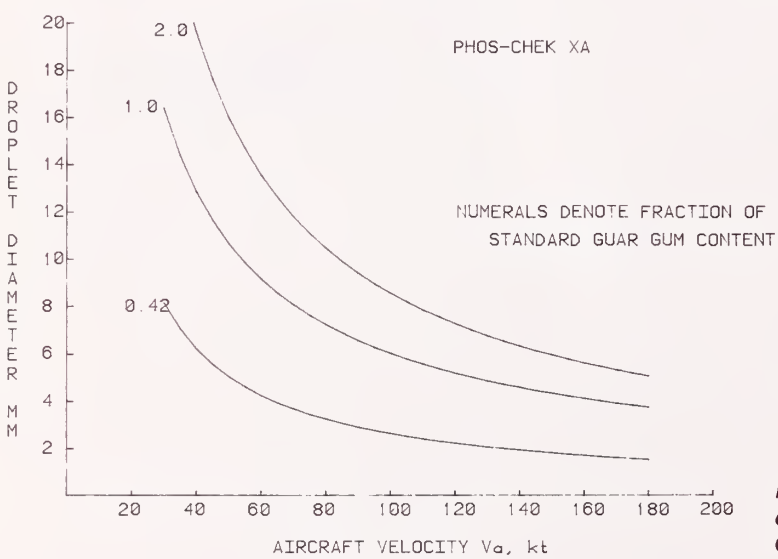

Figure 24.—Droplet diameter as a function of aircraft velocity for several concentrations of Phos-Chek XA.

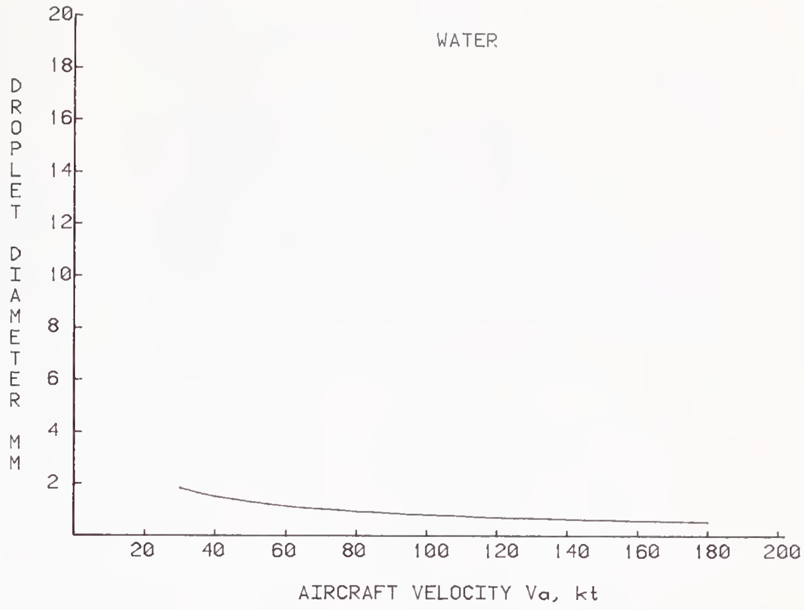

Figure 25.—Droplet diameter as a function of aircraft velocity for water.

DISCUSSION

From the graphs of figures 19 to 24, it is possible to predict the concentration that would yield a particular value of d_m when release occurs at some particular airspeed. Table 1 gives examples of such predictions. When tanker base equipment mixes concentrate with water at the time of loading the aircraft, the composition could be adjusted according to the expected airspeed and altitude at the point of release.

On a few occasions, full-scale, cup-grid field tests have been conducted, usually for the primary purpose of calibrating aircraft/tank performance, during which short-term retardants were used, as well as long-term retardants and water. Gelgard was used in some 1972 tests, but data appropriate to the comparisons being made here are not available. The particular drop tests cited in tables 2 and 3 include those in which Fire-Kill II and other fluids were dropped under the same conditions of airspeed and altitude during the several days of testing represented. The drops marked by asterisks illustrate the increasing total area of coverage as aircraft velocity increases. This effect overcomes (table 2) the expected decrease of total area as height decreases. At the same altitude and airspeed, Fire-Kill II coverages are comparable to those of Phos-Chek 259 and Phos-Chek XA. Compared to water, Fire-Kill II covers somewhat smaller total areas, with the rate of coverage shifted to higher values.

Table 1.—Concentrations needed to yield 3-mm and 5-mm droplet sizes

	Concentration, weight percent						
Retardant	**Airspeed 60 knots**		**Airspeed 90 knots**		**Airspeed 120 knots**		**Recommended use level**
	3 mm	*5 mm*	*3 mm*	*5 mm*	*3 mm*	*5 mm*	*Wt %*
Absorbex	0.15	0.45	0.3	2.3	1.	3.	0.5 to 0.66
Fire-Kill II	.2	1.	.5	2.	1.3	3.	.5 to .75
Fire-Trol STP	.4	.7	.6	1.	.8	2.5	.5 to .66
Short-Stop	.1	.3	.25	.5	.3	.7	.5 to .75
Tenogum	.12	.2	.15	.5	.35	1.	.35

Table 2.—Results of drop tests at the Northern Forest Fire Laboratory grid (Bell 206 helicopter, 90-gallon Los Angeles County tank, July 1981)

Retardant	Nominal Speed	Nominal Alt.	Total area	Coverage, gal/100 ft² 0-0.05	0.05-0.5	0.5-0.9	1-1.9	2-2.9	3-3.9	4-4.9
	Knots	*Ft*	*Ft²*	Percent of total area						
Water	30	150	11,000	17	30	19	26	7	1	0
*FK II	30	150	6,000	7	23	30	34	3	3	0
Water	50	120	19,400	18	48	27	7	0	0	0
*FK II	50	120	18,900	20	49	19	11	0	1	0
PC 259	50	120	17,500	24	44	17	14	1	0	0
PC 259	50	120	14,300	21	39	15	23	2	0	0
*FK II	65	100	22,600	25	55	16	4	0	0	0
PC 259	65	100	24,400	23	56	16	5	0	0	0
PC XA	65	100	25,400	27	55	12	6	0	0	0

*See text for significance.

Table 3.—Results of drop tests at the Northern Forest Fire Laboratory grid (Bell 205 helicopter, Los Angeles County tank, 1982 modifications, May 1982)

Retardant	Nominal Speed	Nominal Alt.	Volume	Total area	Coverage, gal/100 ft² 0-0.05	0.05-0.5	0.5-0.9	1-1.9	2-2.9	3-3.9	4-4.9	5-5.9	6-5.9	7-7.9	8-8.9	9-9.9	10
	Knots	*Ft*	*gal*	*Ft²*	Percent of total area												
Water	50	70	173	15,775	17.7	43.7	11.3	11.7	6.5	5.9	0.6	0.6	1.3	0	0.6	0	0
Water	50	70	345	26,675	15.5	39.0	9.7	15.9	6.2	4.4	2.6	1.8	2.2	1.3	0.4	0	0.9
*FK II (0.25)	50	70	173	13,775	16.3	36.2	11.6	14.7	5.8	5.1	5.8	2.2	1.5	0.7	0	0	0
PC 259	70	70	173	17,575	18.3	40.7	17.1	11.9	6.3	4.0	0.6	1.1	0	0	0	0	0
*FK II (0.25)	70	70	173	17,800	17.8	40.0	12.9	16.3	6.7	4.5	1.1	0	0.6	0	0	0	0
Water	70	120	345	29,625	8.9	30.0	25.5	30.5	4.4	0.7	0	0	0	0	0	0	0
*FK II (0.25)	70	120	173	36,625	0.8	67.4	15.3	13.2	3.3	0	0	0	0	0	0	0	0

*See text for significance.

During informal tests of Fire-Kill I in August of 1979 (Calif. Division of Forestry, Santa Rosa, Calif.) and the cup-grid tests of Fire-Kill II in July 1981 (Northern Forest Fire Laboratory, Missoula, Mont.), subjective opinions formed by experienced observers indicated that use-level concentrations yield well-formed clouds of droplets and result in wetting of grassy or brushy fuels that would contribute significantly to fire suppression.

It is especially important to remember that the d_m is not a singular description of a large portion of a droplet cloud. It is a convenient, derived number that relates to the position along the droplet size continuum of the curve (envelope) of the frequency of occurrence of all sizes. The performance expected of long-term retardants includes circumstances in which a short-term material could not suffice. Short-term retardant droplet diameters are only one-half to one-third those of, for example, Phos-Chek XA, so that they would not be expected to penetrate mature forest canopies as well. Also, if ground suppression activity cannot follow the airdrop in a short time, the short-term retardant's effects may be completely overcome by the fire. The less viscous short-term materials give adequate surface films on the fuel, and at the same time, evaporative loss is strongly inhibited. The laboratory characterization of the materials provides quantitative measures of the visco-elastic properties and allows the judgment of whether the viscosity and elasticity of a new material are sufficient. It also offers the chance to establish the use level concentration at an effective but economical value. For example, if a 3-mm mass median diameter is appropriate, and average airspeeds are in the order of 90 knots, then table 1 would infer that Absorbex, Short-Stop, and Tenogum could be formulated using about half as much thickener as is presently recommended.

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U.S. GOVERNMENT PRINTING OFFICE: 1983—676-032/53 REGION No. 8